

# VACUUM PRESSURE RISE WITH INTENSE ION BEAMS IN RHIC\*

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## Abstract

When RHIC is filled with bunches of intense ion beams a pressure rise is observed. The pressure rise exceeds the acceptable limit for operation with the design intensities. Observations of events leading to a pressure rise are summarized. Relevant parameters include ion species, charge per bunch, bunch spacing, and the location in the ring. Effects that contribute to a pressure rise are discussed, including beam gas ionization and ion desorption, loss-induced gas desorption, and electron desorption from electron clouds.

## 1 INTRODUCTION

During the RHIC 2001 gold run first attempts were made to double the bunch number from 55 to 110 by reducing the bunch spacing from 214 ns to 107 ns. In these attempts pressure bumps were observed with pressures high enough to prevent operation. Fig. 1 shows two fills with 110 bunches per ring. The first one is aborted by the vacuum system before the second ring is filled completely. The beam permit is pulled at pressures above  $10^{-7}$  Torr. The second pressure elevation, about 20 min later, is from a fill with intensities reduced by 10%. In this case the beam is not aborted by the vacuum system but from beam losses near the end of the ramp.

A total of 15 cases occurred [1–3], where the vacuum system aborted the beam due to pressures exceeding the set limit. Although the data are limited, the observations can be summarized with respect to certain parameters:

**Ion species** – Only gold beam was aborted by the vacuum system. However, for proton beams the abort threshold was raised from  $10^{-7}$  to  $10^{-6}$  Torr in the warm interaction regions, and pressures higher than  $10^{-7}$  Torr were seen in some instances. Gold beam pressures at times exceeded  $10^{-4}$  Torr and even a raised threshold would not have prevented a beam abort. Some gold cases look like a vacuum instability, other cases; gold and protons, show the pressure saturating.

**Charge per bunch and bunch spacing** – The pressure rise is clearly intensity-dependent. A single beam with 214 ns bunch spacing was never aborted. With two beams stored, the same total intensity threshold was found with 55 and 110 bunches per ring, suggesting a total intensity limit. However, in one case a single beam with 107 ns bunch spacing was aborted with a total intensity below what could be stored with 214 ns spacing shortly thereafter.

**Location in the ring** – Large pressure bumps were only observed in the warm interaction regions. There, the pressure without beam is about  $10^{-9}$  Torr. Parts of the warm

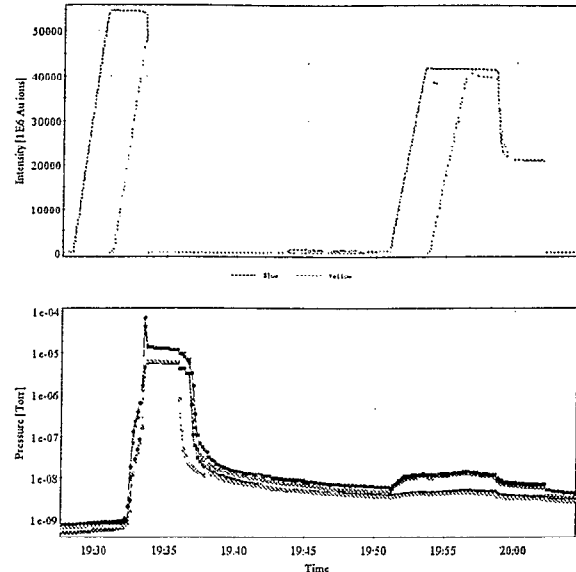


Figure 1: Beam intensities (upper part) and pressure in an interaction region (lower part). Shown are two attempt to fill both rings with 110 bunches.

interaction regions were not baked and may therefore have large coefficients for ion or electron desorption. The average beam pipe diameter in the warm regions is 12 cm, while it is 7 cm in the cold arcs. Beam aborts that happened when two beams were stored were usually triggered by vacuum readings from regions that are shared by both beams.

In the following we investigate if ion desorption, beam losses, or beam induced electron clouds could be essential in raising the pressure.

## 2 ION DESORPTION

Ions created from the interaction of the beam with the rest gas in the beam pipe can travel to the pipe walls and desorb molecules, which in turn can be ionized by the beam. The process can run away if the product of the number of circulating particles with the desorption coefficient  $\eta$  (the number of molecules released for an ion hitting the wall) exceeds a threshold.

The ionization cross section  $\sigma_j$  for a beam particle of charge  $Ze$  hitting a molecule  $j$  can be written as [4, 5]

$$\sigma_j = 1.874 \cdot 10^{-24} \text{ m}^2 \frac{Z^2}{\beta^2} (M_j^2 x + C_j) \quad (1)$$

where  $M_j^2$  and  $C_j$  are coefficients specific to the molecule and  $x = 2 \ln(\beta\gamma) - \beta^2$  is a function of the relativistic beam parameters  $\beta$  and  $\gamma$ . For a given number of circulating particles  $N_a N_b$  (see Tab. 1) one can compute a critical desorption coefficient  $\eta_{crit}$  as [6]

$$\eta_{crit} = \frac{\pi^2}{4} \frac{1}{N_a N_b f_{rev} \sigma L^2} c \quad (2)$$

\* Work supported by US DOE under contract DE-AC02-98CH10886.

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where  $f_{rev}$  is the revolution frequency,  $c$  is the beam tube conductance and  $2L$  the distance between vacuum pumps. If the actual desorption coefficient is larger than this number, a vacuum instability results and the pressure can rise without bounds.

We consider two molecules,  $H_2$  and  $CO$ . Measurements show that  $H_2$  is the dominant rest gas in the warm section of RHIC, but heavier molecules can be desorbed from the wall through beam losses.  $CO$  is a good representative for those heavier molecules. In Tab. 1 the ionization cross sections are shown using the coefficients from Ref. [7]. The table also shows the computed critical desorption coefficients  $\eta_{crit}$  for the two molecules for both gold and proton beams. The smallest desorption coefficient is obtained for gold beams with  $CO$  rest gas. Not considered here is the case of ionization and desorption of different rest gas ions. This case is treated, for example, in Ref. [8].

To get an estimate for actual desorption coefficients, we compute the energy  $E_{ion}$  of an ion with a single electron charge moving in the beam potential to the wall [9]:

$$E_{ion} = \frac{e^2 N_a}{2\pi\epsilon_0 L_{sep}} \ln\left(\frac{r}{\sigma_r}\right) \quad (3)$$

where  $r$  is the beam pipe and  $\sigma_r$  the rms beam radius.  $L_{sep}$  is the bunch separation. For beams with parameters like in Tab. 1,  $E_{ion}$  is not larger than 25 eV. Eq. (3) can overestimate the energy with small beam pipes. With such small energies and unbaked stainless steel,  $\eta_{H_2} = 1.0$  and  $\eta_{CO} = 0.5$  may be reasonable values [6].

From these calculations, an ion desorption instability seems only possible with gold beams and a  $CO$ -like rest gas component. Since molecules like  $CO$  are only a small fraction of the rest gas without beam, injection losses may be needed to create a large enough population in the pipe.

Table 1: Beam parameters and computed maximum allowable desorption coefficients  $\eta_{crit}$  for  $H_2$  and  $CO$  in the common warm sections for both gold and proton beams.

| parameter                        | unit                           | Au <sup>79+</sup>    | p <sup>+</sup>       |
|----------------------------------|--------------------------------|----------------------|----------------------|
| atomic number $Z$                | ...                            | 79                   | 1                    |
| mass number $A$                  | ...                            | 197                  | 1                    |
| relativistic $\gamma$            | ...                            | 10.52                | 25.94                |
| revolution freq. $f_{rev}$       | Hz                             | $7.8 \cdot 10^4$     |                      |
| cross section $\sigma_{H_2}$     | m <sup>2</sup>                 | $1.3 \cdot 10^{-19}$ | $2.2 \cdot 10^{-23}$ |
| cross section $\sigma_{CO}$      | m <sup>2</sup>                 | $5.8 \cdot 10^{-19}$ | $1.0 \cdot 10^{-22}$ |
| pressure $p_0$                   | Torr                           | $1.0 \cdot 10^{-9}$  |                      |
| temperature $T$                  | K                              | 300                  |                      |
| particles per bunch $N_a$        | ...                            | $10^9$               | $10^{11}$            |
| bunches $N_b$                    | ...                            | 110                  |                      |
| tube conductance $c_{H_2}$       | m <sup>4</sup> s <sup>-1</sup> | 0.75                 |                      |
| tube conductance $c_{CO}$        | m <sup>4</sup> s <sup>-1</sup> | 0.25                 |                      |
| pumping speed $S_{H_2}$          | m <sup>3</sup> s <sup>-1</sup> | 0.94                 |                      |
| pumping speed $S_{CO}$           | m <sup>3</sup> s <sup>-1</sup> | 0.31                 |                      |
| space betw. pumps $2L$           | m                              | 14                   |                      |
| desorp. coeff. $\eta_{crit,H_2}$ | ...                            | 35                   | 1959                 |
| desorp. coeff. $\eta_{crit,CO}$  | ...                            | 2.5                  | 140                  |

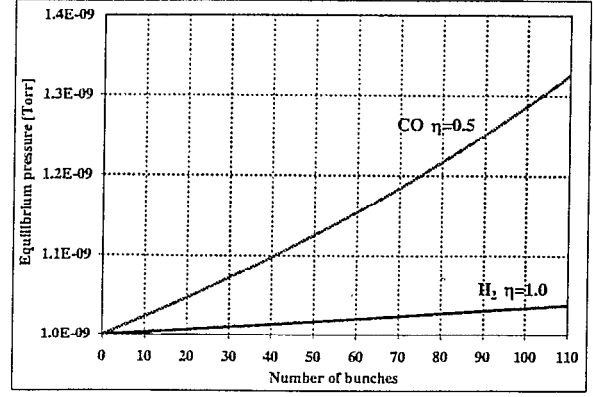


Figure 2: Equilibrium pressure as a function of the bunch train length  $N_b$  for the rest gases  $H_2$  and  $CO$  with gold beams. Note the linear pressure scale.

The equilibrium pressure can be approximated by [10]

$$p = p_0 \left(1 - \frac{\sigma \eta N_a N_b f_{rev}}{c \lambda^2}\right)^{-1} \quad (4)$$

where  $\lambda$  is the smallest root of the transcendental equation  $\lambda \tan(\lambda L) = S/c$ , and  $S$  the pumping speed. In Fig. 2 the equilibrium pressures are shown as a function of the bunch number  $N_b$  for gold beams with  $10^9$  ions per bunch. In both cases only an insignificant pressure rise is expected.

### 3 LOSS INDUCED DESORPTION

The immediate pressure rise due to losses is

$$\Delta p = \frac{kT}{2\pi r^2} \frac{dN}{dl} \eta_l, \quad (5)$$

where  $k$  is the Boltzmann constant,  $r$  the beam pipe radius,  $dN/dl$  the particle loss per unit length, and  $\eta_l$  the desorption coefficient for lost beam particles. If we would assume  $\eta_l = 3 \cdot 10^5$ , and a 5% loss of all bunches within 10 meters in the warm regions, the pressure would rise by  $2 \cdot 10^{-7}$  and exceed the abort threshold. Large uncertainties exist in the knowledge of  $\eta_l$  and the assumed beam loss, although possible, is unusually high. We also neglected that the injection of 110 gold bunches takes about 2 min during which time the pumps will counteract the immediate pressure rise.

The losses may create a population of heavier molecules in the beam pipe, which can accelerate an ion desorption instability. It has also been suggested that positive ions created from losses can extend the lifetime of an electron cloud, which in turn can raise the pressure [1].

Beam losses from inelastic rest gas scattering could, in principle, lead to a vacuum instability if they deteriorate the vacuum so much that more beam losses are created. The beam losses due to inelastic scattering are

$$\frac{1}{N_a N_b} \frac{dN}{dt dl} = -\frac{p}{kT} f_{rev} \sigma_{ie} \quad (6)$$

where  $\sigma_{ie}$  is the cross section for inelastic scattering, for which we take as an approximate value  $\sigma_{ie} = 2 \cdot 10^{-28}$  m<sup>2</sup> [11]. With this we obtain a beam loss  $dN/N_a N_b$  of less than 1% in one hour, for the whole ring, and for pressures of  $10^{-7}$  Torr. This effect is small compared to other beam loss effects.

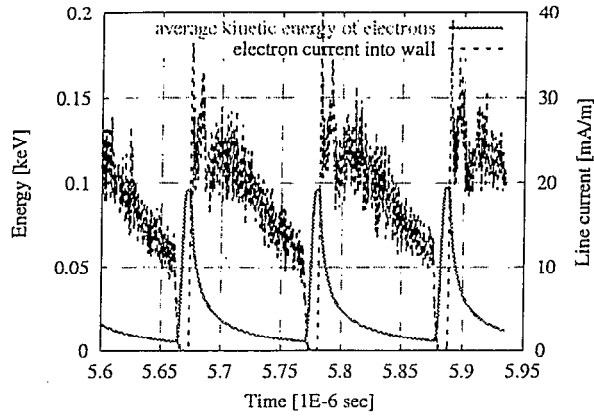


Figure 3: Average kinetic energy of electrons and current into the beam pipe wall from an electron cloud simulation. The passage of three bunches is shown after the cloud density reached saturation.

#### 4 ELECTRON DESORPTION

A pressure rise could also be caused by an electron cloud. The electrons in a cloud bombard the wall and could thus desorb molecules. To study the electron cloud experimentally, the coherent tune change along a bunch train was measured [12]. From the measured tune shift the cloud density can be estimated.

In simulations the estimated cloud density could be obtained with somewhat higher bunch charges and the average beam pipe radius [12]. However, the cloud density with the warm region beam pipe radius was found to be an order of magnitude lower. Fig. 3 shows the average kinetic energy of electrons and the electron current into the wall for a simulation that approximately reproduces the estimated electron cloud density. In saturation, we have an average kinetic electron energy  $E_e$  of about 50 eV, and an average line current into the wall  $dI_e/dl$  of about 15 mA/m. This is only a very crude estimate. Electron cloud simulation results can be very sensitive to small changes in a number of input parameters [12]. For electrons of 50 eV energy we assume a desorption coefficient of  $\eta_e = 0.05$  [1, 13].

The gas load due to the electron desorption  $Q_e$ , created between two pumps, and the resulting equilibrium pressure  $p$ , if dominated by the electron desorbed gas, can be approximated by

$$p = \frac{Q_e}{S} = \frac{2L}{S} \frac{kT}{e} \frac{dI_e}{dl} \eta_e \quad (7)$$

Using the pumping speed for CO, we obtain  $p = 3 \cdot 10^{-6}$  Torr, above the threshold for an beam abort. Dynamic effects are neglected here.

#### 5 SUMMARY

Ion desorption, losses and electron desorption could contribute to the pressure rises observed in RHIC. An ion desorption instability seems only possible with gold beams after CO like molecules were released from the wall due to beam losses. The pressure rise from beam losses alone may

be sufficient to exceed the vacuum abort threshold. It is also possible that electron clouds caused the pressure rises. All our estimates have large errors and more experimental data are needed for a better understanding.

Baking, currently under way, may be an effective cure. It should lower the desorption coefficients for ions, lost beam particles and electrons. A number of electron detectors are installed in the warm regions along with solenoids in one interaction region to further investigate electron clouds. The installation of more pumping speed will also improve the situation.

#### 6 ACKNOWLEDGMENTS

The authors would like to thank for support and discussions: G. Arduini, O. Boine-Frankenheim, M. Furman, O. Gröbner, E. Mahner, N. Hilleret, F. Pilat, M. Pivi, A. Rossi, G. Rumolo, S. Tepikian, W.C. Turner, and F. Zimmermann.

#### 7 REFERENCES

- [1] S.Y. Zhang, "RHIC vacuum pressure bump", BNL C-A/AP/67 (2002).
- [2] H.-C. Hseuh, "Vacuum data analysis and improvement plan", RHIC Retreat 2002, <http://www.cad.bnl.gov/RHIC/retreat2002> (2002).
- [3] H.-C. Hseuh, L. Smart, S.Y. Zhang, "Analysis of beam induced pressure increases in the RHIC warm vacuum sections", these proceedings.
- [4] M. Inokuti, "Inelastic collisions of fast charged particles with atoms and molecules – the Bethe theory revisited", Rev. Mod. Phys. Vol. 43, No. 3 pp. 297-347 (1971).
- [5] W.C. Turner, unpublished note (1999).
- [6] O. Gröbner, "Dynamic outgassing", in CAS Vacuum Technology, Snekersten, Denmark, CERN 99-05 (1999).
- [7] F.F. Rieke and W. Prepejchal, Phys. Rev. A Vol. 6 No. 4, p 1507 (1972).
- [8] W.C. Turner, "Ion desorption stability in superconducting high energy physics proton colliders", J. Vac. Sci. Technol. A 14(4), pp 2026 (1996).
- [9] G. Rumolo and F. Zimmermann, "Interplay of ionization and sputtering with the electron cloud", CERN-SL-2001-014 AP (2001).
- [10] O. Gröbner and R.S. Calder, "Beam induced gas desorption in the CERN Intersecting Storage Rings", proceedings of the 1973 Particle Accelerator Conference, San Francisco (1973).
- [11] D. Trbojevic, "The beam lifetime and emittance growth in RHIC under normal operating conditions and with a hydrogen gas jet", BNL RHIC/AP/136 (1997).
- [12] W. Fischer, J.M. Brennan, M. Blaskiewicz, and T. Satogata, "Electron cloud measurements and simulations for RHIC", proceedings of the ECLOUD02 workshop at CERN, BNL CAD/AP/71 (2002).
- [13] F. Billard, N. Hilleret, G. Vorlauffer, "Some results on the electron induced desorption yield of OFHC copper", CERN LHC/VAC/FB/NH/GV00-32 (2000).